Wind Turbine Gearbox Oil Filtration and Condition Monitoring


Photo by Dennis Schroeder, *NREL 19018*

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Agenda

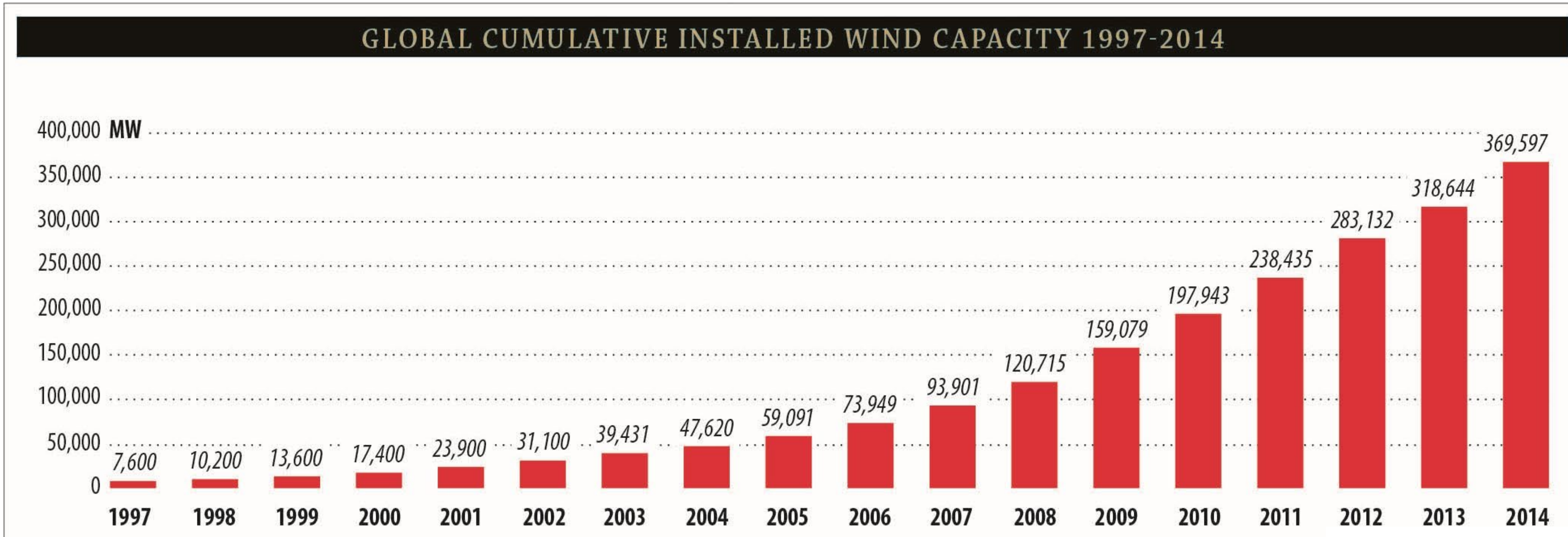
- Introduction
- Gearbox Oil Filtration
- Gearbox Oil Condition Monitoring (CM)
- Future Research and Development (R&D) Opportunities

U.S. Department of Energy 1.5-MW Wind Turbine, *Photo by Lee Jay Fingersh, NREL 17245*

Introduction

- Global Wind Energy
- Average Downtime of Turbine Subsystems
- Oil Filtration and Condition Monitoring
- Operation and Maintenance of Wind Plants

Global Wind Energy



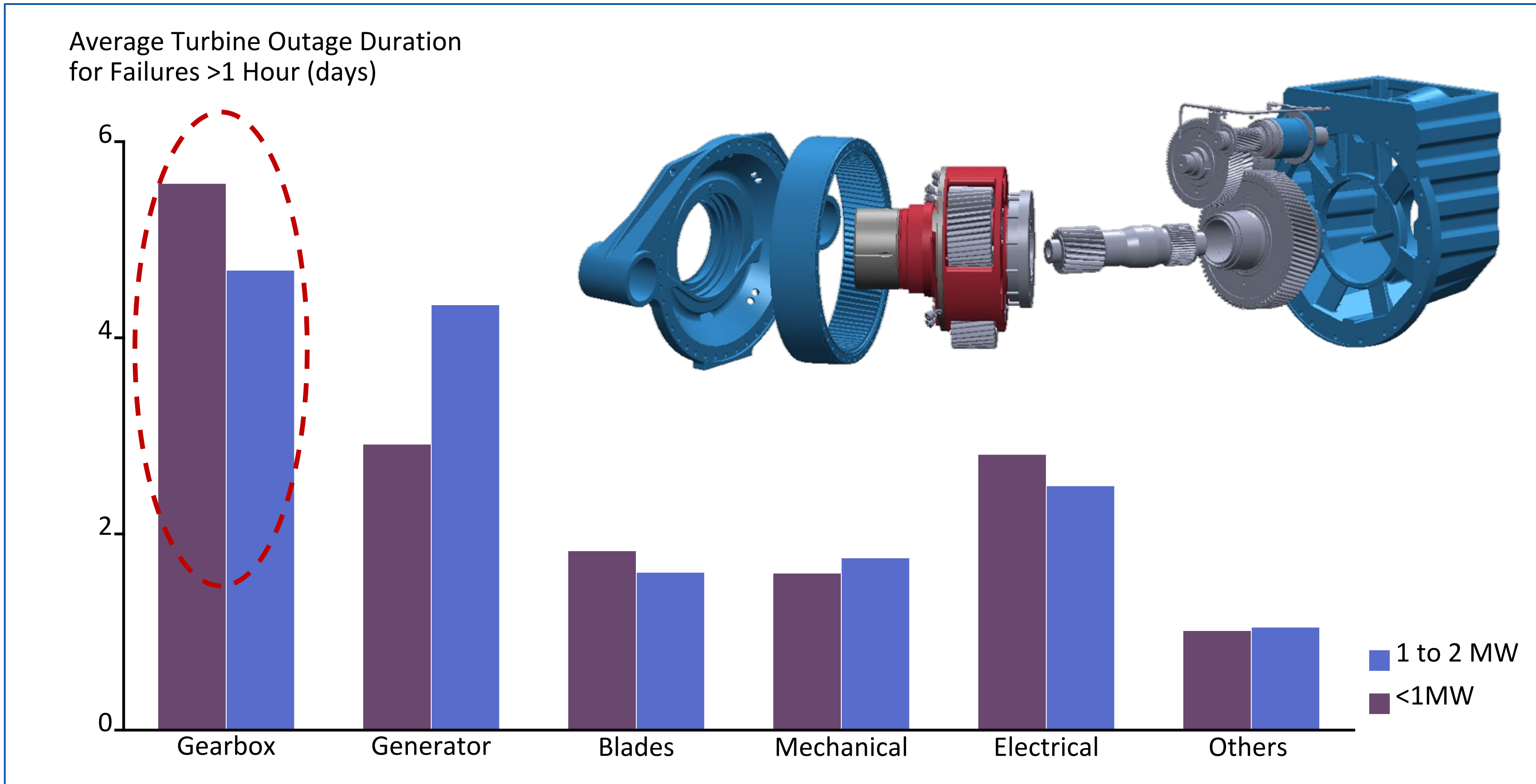
Source: GWEC [1]

Photo by Iberdrola Renewables, Inc., *NREL 16706*

Photo by HC Sorenson, *NREL 17856*

Average Downtime of Turbine Subsystems

- Premature component failures, led by gearbox, increase operation and maintenance (O&M) costs, downtime, and cost of energy (COE)



Bar Chart Source: Chamberlain, K. [2]
Gearbox Illustration: NREL

Oil Filtration and Condition Monitoring

- Filtration [3]
  - Prolonged lifetime of components
  - Prolonged lifetime of oil
  - Fewer unplanned production stops
  - Longer machine service intervals
  - Fewer man hours needed for maintenance
- Condition Monitoring [4]
  - Early deterioration detection to avoid catastrophic failure
  - Accurate damage evaluation to enable cost-effective maintenance practices (proactive instead of reactive)
  - Increase turbine availability and reduce operation and maintenance costs

Test Turbine at Ponnequin/*Photo by Jeroen van Dam, NREL 19257*

Operation and Maintenance of Wind Plants

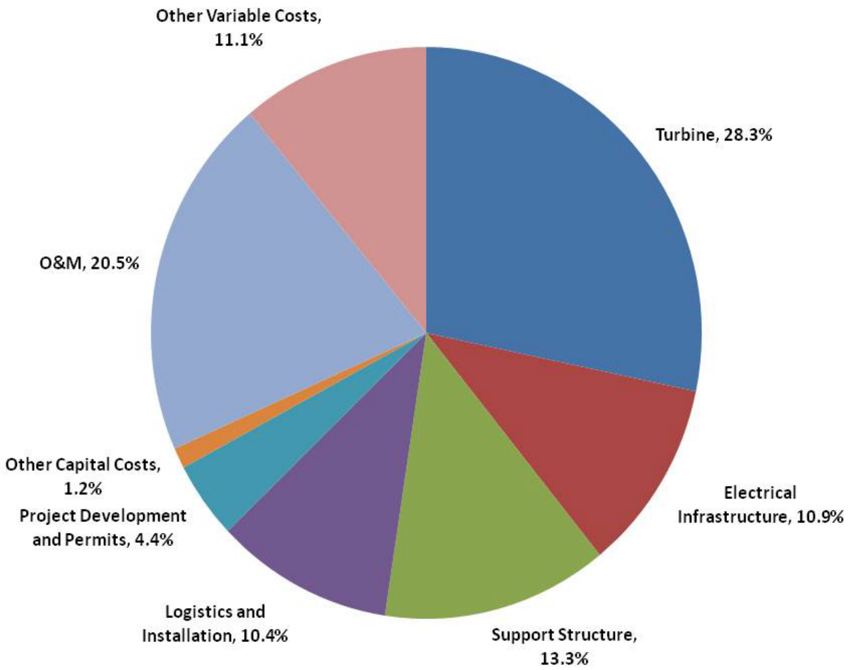
- Operation and maintenance (O&M) research needs:
  - The majority of the wind turbines (~370 GW) installed worldwide are out of warranty
  - A 1% performance improvement: ~$1,165.5 million additional revenue [assumed: 30% capacity factor, $120/megawatt-hour (MWh) electricity rate]
  - Extremely high replacement costs for most subsystems

Tehachapi Pass Wind Farm in California /*Photo by David Hicks, NREL 18453*

- Example replacement costs for components of a 5-megawatt (MW) wind turbine [5]
  - Rotor: $1.9–2.3 million
  - Blade: $391,000–547,000
  - Blade bearing: $62,500–78,200
  - Gearbox: $628,000
  - Generator: $314,000
  - Electronic modules: $16,000

O&M of Wind Plants (*Cont.*)

- O&M cost reduction opportunities:
  - ~21% for offshore plants
  - ~11% for land-based plants
  - Further reductions possible if O&M practices are improved by:
    - Considering performance monitoring for operation
    - Introducing condition-based maintenance
- Extending gearbox service life and improving availability through oil filtration and CM can reduce O&M costs, more important for offshore wind



Estimated life cycle cost breakdown for a baseline offshore wind project [6]

Gearbox Oil Filtration

- Typical practices
- Discussions

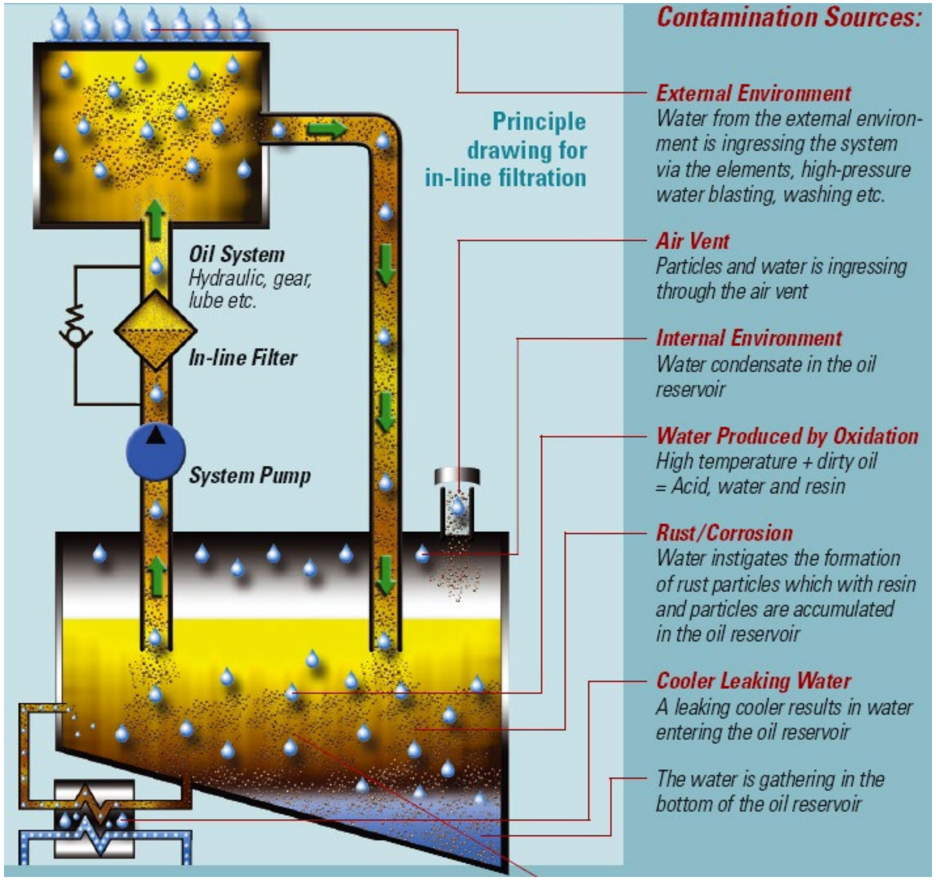


Illustration Source: Thomsen C.J. [3]

Incentive for Oil Filtration

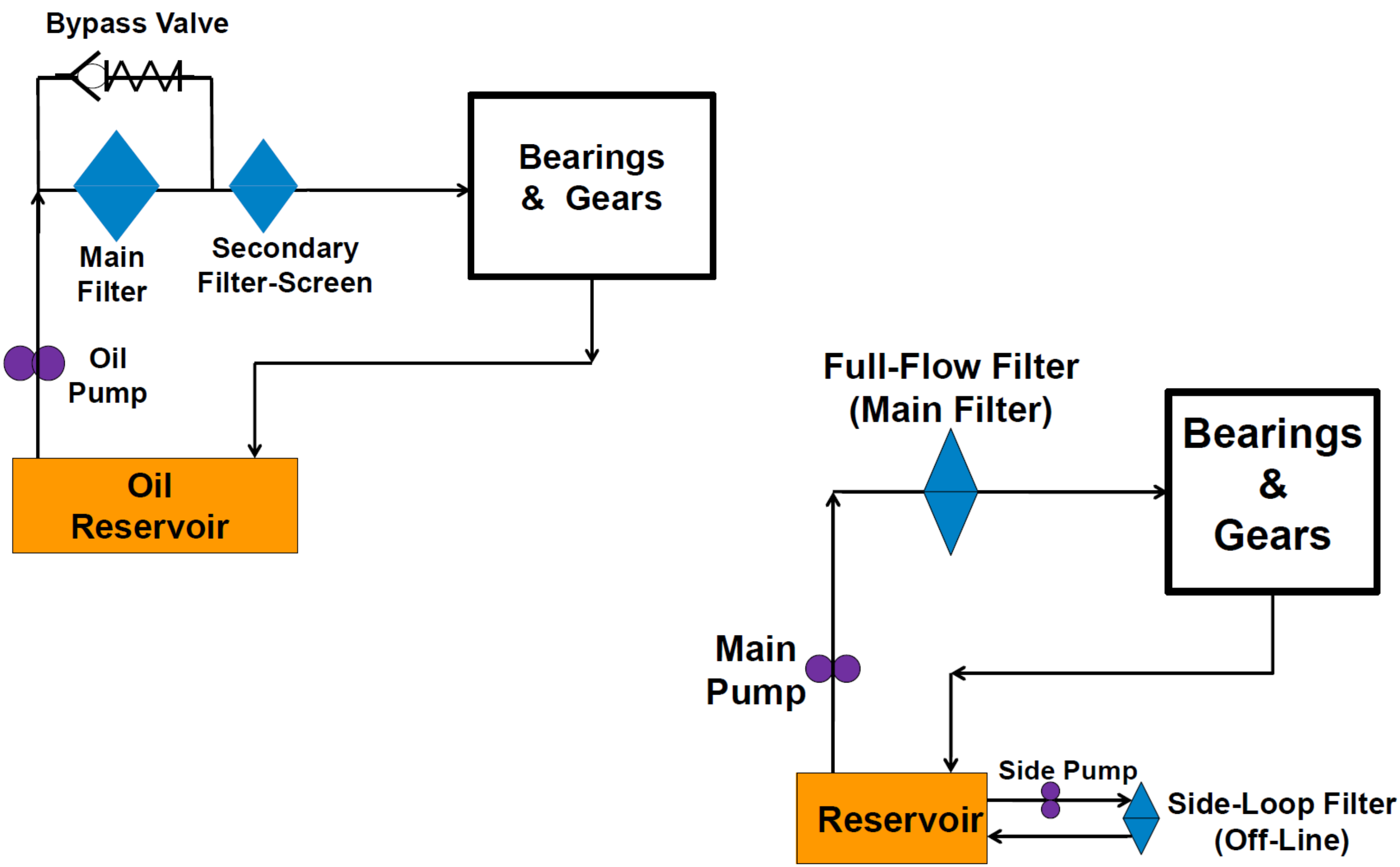
NEW CLEANLINESS LEVEL (ISO CODE)

CURRENT CLEANLINESS (ISO CODE)	20/17		19/16		18/15		17/14		16/13		15/12		14/11		13/10		12/9		11/8		10/7	
26/23	5	3	7	3.5	9	4	>10	5	>10	6	>10	7.5	>10	9	>10	>10	>10	>10	>10	>10	>10	>10
	4	2.5	4.5	3	6	3.5	6.5	4	7.5	5	8.5	6.5	10	7	>10	9	>10	10	>10	>10	>10	>10
25/22	4	2.5	5	3	7	3.5	9	4	>10	5	>10	6	>10	7	>10	9	>10	>10	>10	>10	>10	>10
	3	2	3.5	2.5	4.5	3	5	3.5	6.5	4	8	5	9	6	10	7.5	>10	9	>10	>10	>10	>10
24/21	3	2	4	2.5	6	3	7	4	9	5	>10	6	>10	7	>10	8	>10	10	>10	>10	>10	>10
	2.5	1.5	3	2	4	2.5	5	3	6.5	4	7.5	5	8.5	6	9.5	7	>10	8	>10	10	>10	>10
23/20	2	1.5	3	2	4	2.5	5	3	7	3.5	9	4	>10	5	>10	6	>10	8	>10	9	>10	>10
	1.7	1.3	2.3	1.5	3	2	3.7	2.5	5	3	6	3.5	7	4	8	5	10	6.5	>10	8.5	>10	10
22/19	1.6	1.3	2	1.6	3	2	4	2.5	5	3	7	3.5	8	4	>10	5	>10	6	>10	7	>10	>10
	1.4	1.1	1.8	1.3	2.3	1.7	3	2	3.5	2.5	4.5	3	5.5	3.5	7	4	8	5	10	5.5	>10	8.5
21/18	1.3	1.2	1.5	1.5	2	1.7	3	2	4	2.5	5	3	7	3.5	9	4	>10	5	>10	7	>10	10
	1.2	1.1	1.5	1.3	1.8	1.4	2.2	1.6	3	2	3.5	2.5	4.5	3	5	3.5	7	4	9	5.5	10	8
20/17			1.3	1.2	1.6	1.5	2	1.7	3	2	4	2.5	5	3	7	4	9	5	>10	7	>10	9
			1.2	1.05	1.5	1.3	1.8	1.4	2.3	1.7	3	2	3.5	2.5	5	3	6	4	8	5.5	10	7
19/16					1.3	1.2	1.6	1.5	2	1.7	3	2	4	2.5	5	3	7	4	9	6	>10	8
					1.2	1.1	1.5	1.3	1.8	1.5	2.2	1.7	3	2	3.5	2.5	5	3.5	7	4.5	9	6
18/15							1.3	1.2	1.6	1.5	2	1.7	3	2	4	2.5	5	3	7	4.5	>10	6
							1.2	1.1	1.5	1.3	1.8	1.5	2.3	1.7	3	2	3.5	2.5	5.5	3.7	8	5
17/14									1.3	1.2	1.6	1.5	2	1.7	3	2	4	2.5	6	3	8	5
									1.2	1.1	1.5	1.3	1.8	1.5	2.3	1.7	3	2	4	2.5	6	3.5
16/13											1.3	1.2	1.6	1.5	2	1.7	3	2	4	3.5	6	4
											1.2	1.1	1.5	1.3	1.8	1.5	2.3	1.8	3.7	3	4.5	3.5
15/12													1.3	1.2	1.6	1.5	2	1.7	3	2	4	2.5
													1.2	1.1	1.5	1.4	1.8	1.5	2.3	1.8	3	2.2
14/11															1.3	1.3	1.6	1.6	2	1.8	3	2
															1.3	1.2	1.6	1.4	1.9	1.5	2.3	1.8
13/10																	1.4	1.2	1.8	1.5	2.5	1.8
																	1.2	1.1	1.6	1.3	2	1.6

Hydraulics and Diesel Engines	Rolling Element Bearings
Journal Bearings and Turbo Machinery	Gear Boxes and Other

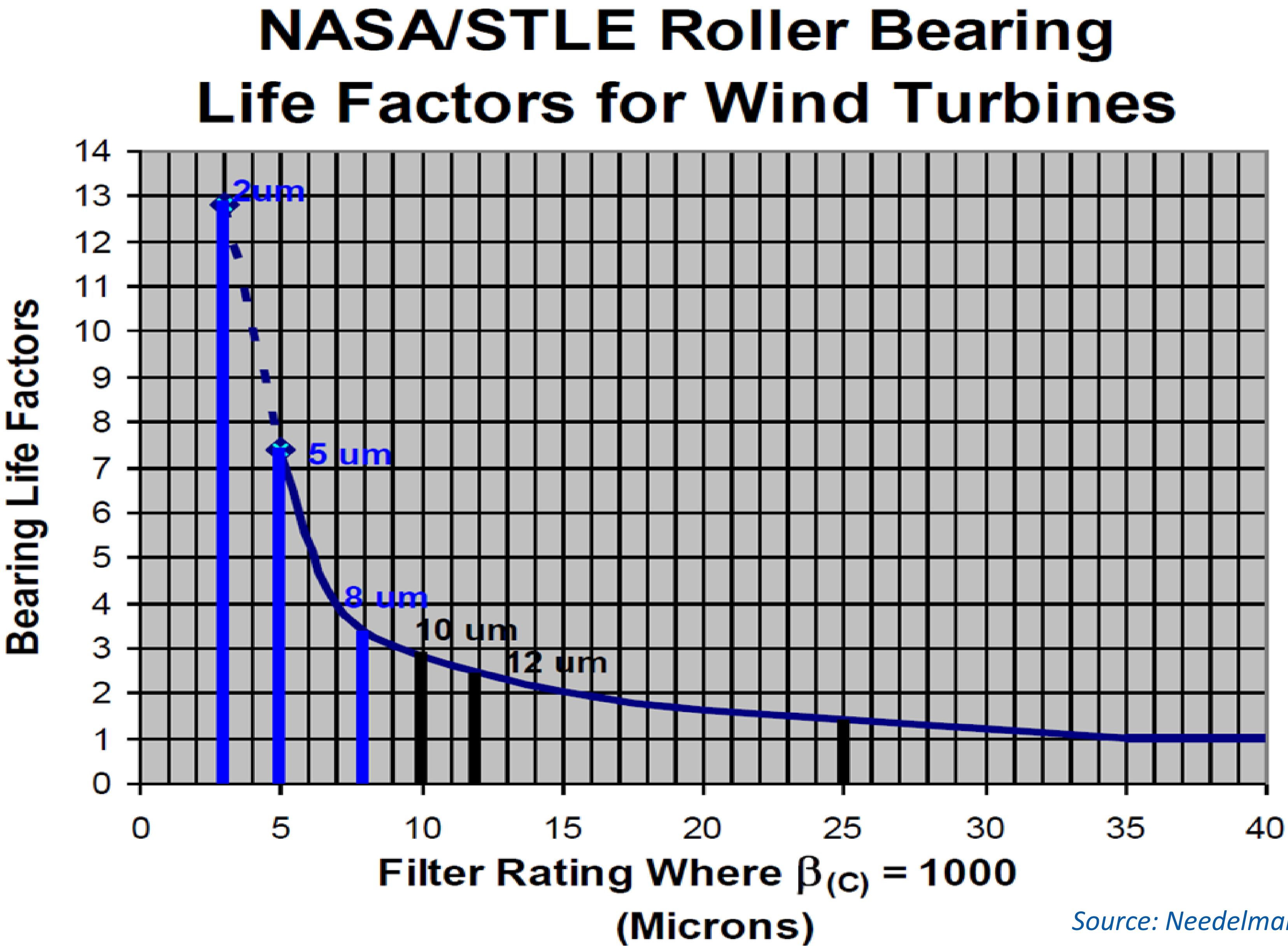
Sources: Noria [7]

Gearbox Filtration: Main- and Offline-loop



Source: Needelman B. [8]

Impacts of Filter Ratings on Bearing Life



Source: Needelman B. [8]

Filter Media Types

	Cellulose	Micro-Fiberglass	Stainless Steel Wire Cloth	Metal Felt
Initial Cost	Low	Moderate	Low to High*	High
Capture Efficiency	Moderate	High	Low to High*	High
Dirt Holding Capacity	Moderate	High	Low to High*	High
Differential Pressure	Low to Moderate	Low to Moderate	Low to High*	Low
Life in a System	High	Low to High*	High	High
Fluid Compatibility	Low	Moderate	High	High
Cleanable	No	No	Yes	Yes

* The performance of stainless steel elements depends on the mesh size and the fluid system requirements.

Source: Swift Filters, Inc. [9]

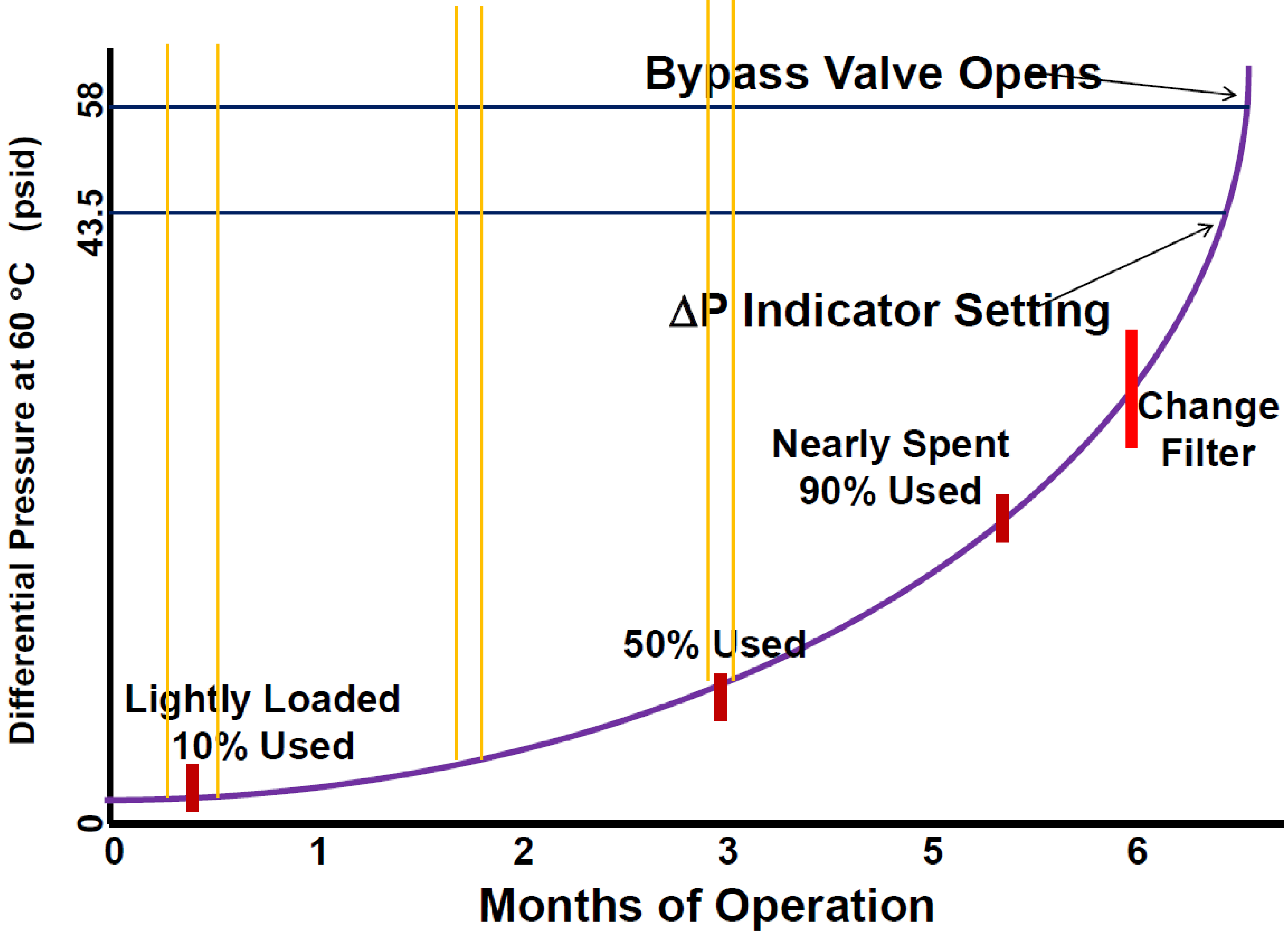
β Ratio

- Modern filter filtration ratios are greater than 200 and a typical recommendation is 1000 [10]

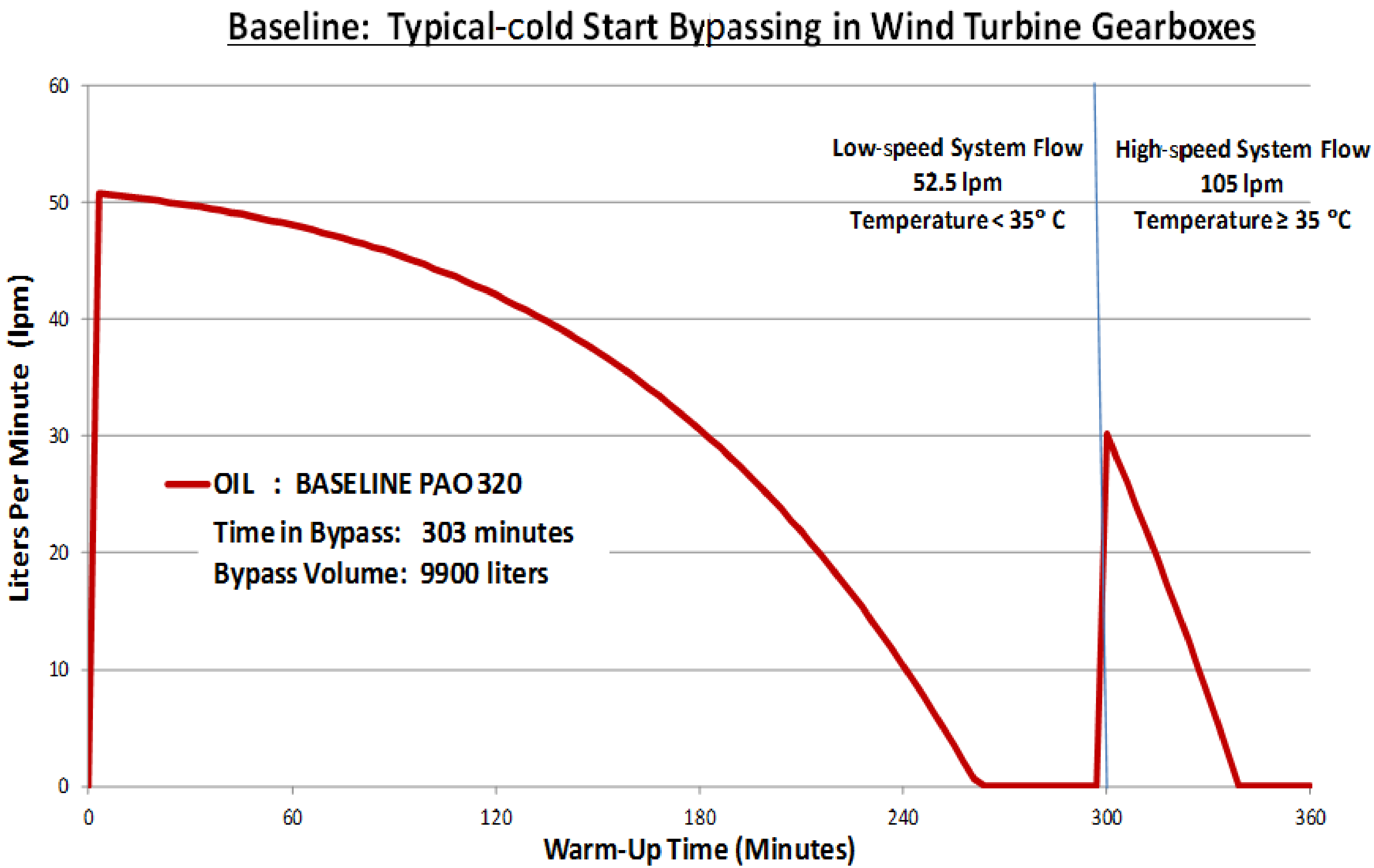
Filtration Ratio (at a given particle size)	Capture Efficiency (at the same particle size)
2	50%
5	80%
10	90%
20	95%
75	98.6%
100	99%
200	99.5%
1000	99.9%

Chart Source: Cummins Filtration [11]

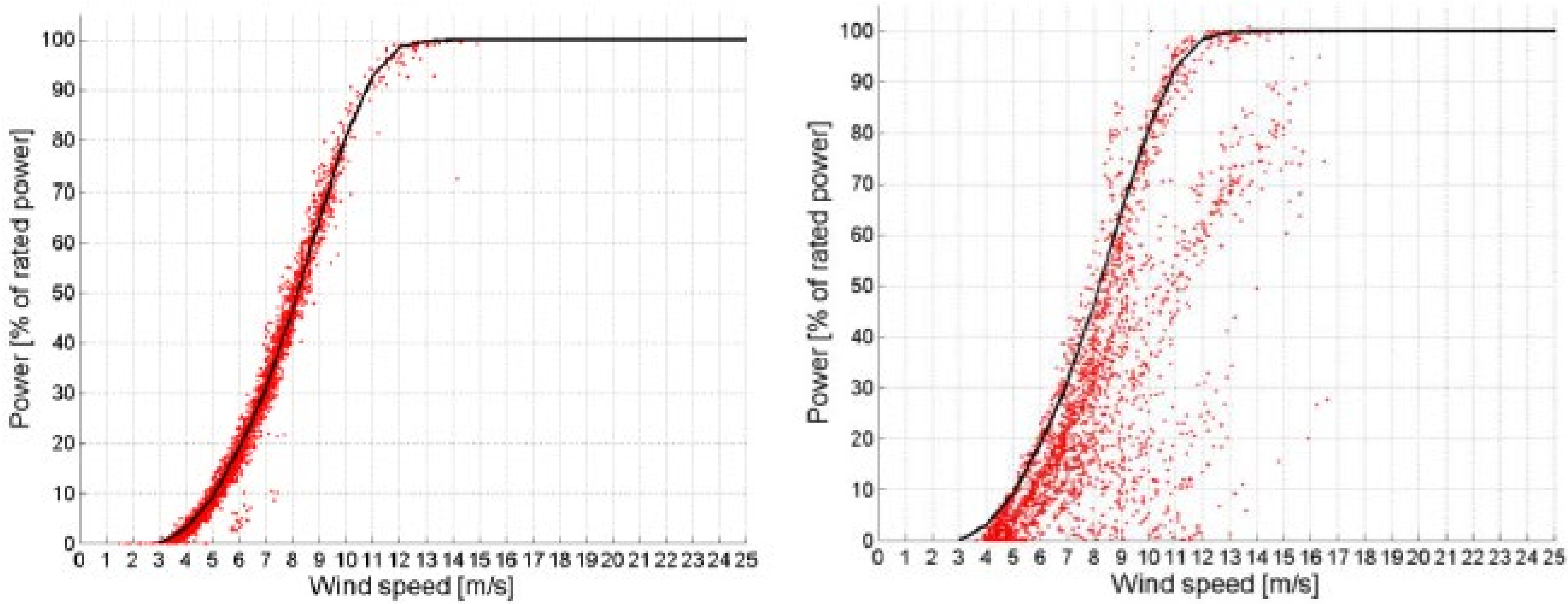
Typical Increase in Flow Restriction [8]



Cold-Start Bypassing Baseline Conditions [8]



Power Performance under Cold Climate



- Power reductions mainly caused by icing on blades and anemometers and wind vanes
- Contributing factor: filtration system cold-starts?

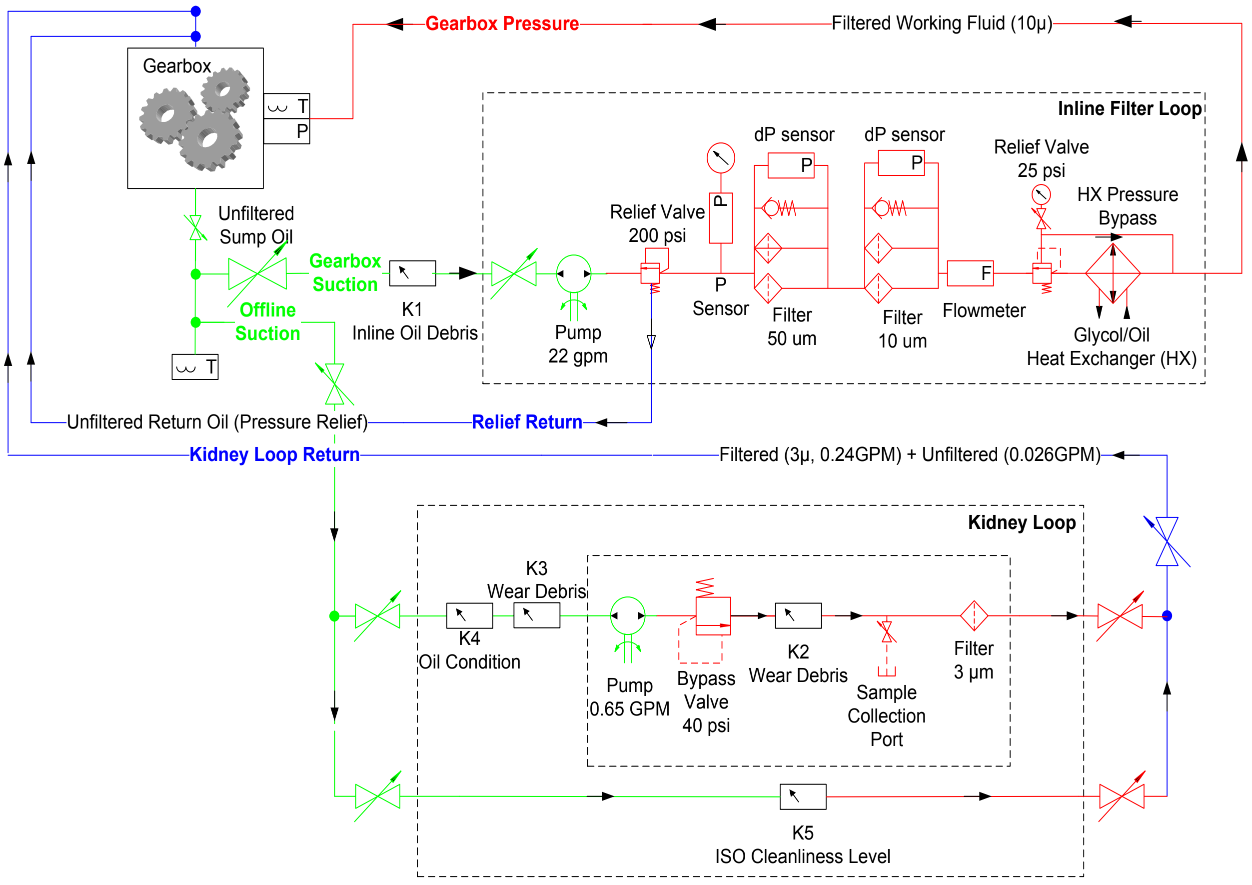
Plots Source: IEA Wind [12]

Discussions

- Main-loop filters:
  - Default option in wind turbine gearboxes
  - Challenges to address [8]
    - Full rated flow through filter leads to possible ΔP problems
    - Collects most contaminant particles, leading to short service life issues
    - Filters may be exposed to cold starts, flow surges, and to mechanical vibrations.
- Offline-loop filters:
  - Optional for end users, plant developers, owners, and operators
  - Advantages [8]
    - When used for continuous operation, low flow rate and complement to main-loop filters
    - Constant flow – no flow surges. Often isolated from mechanical vibration
  - Challenges to address [8]
    - Oil supplier may limit how fine a filter is acceptable

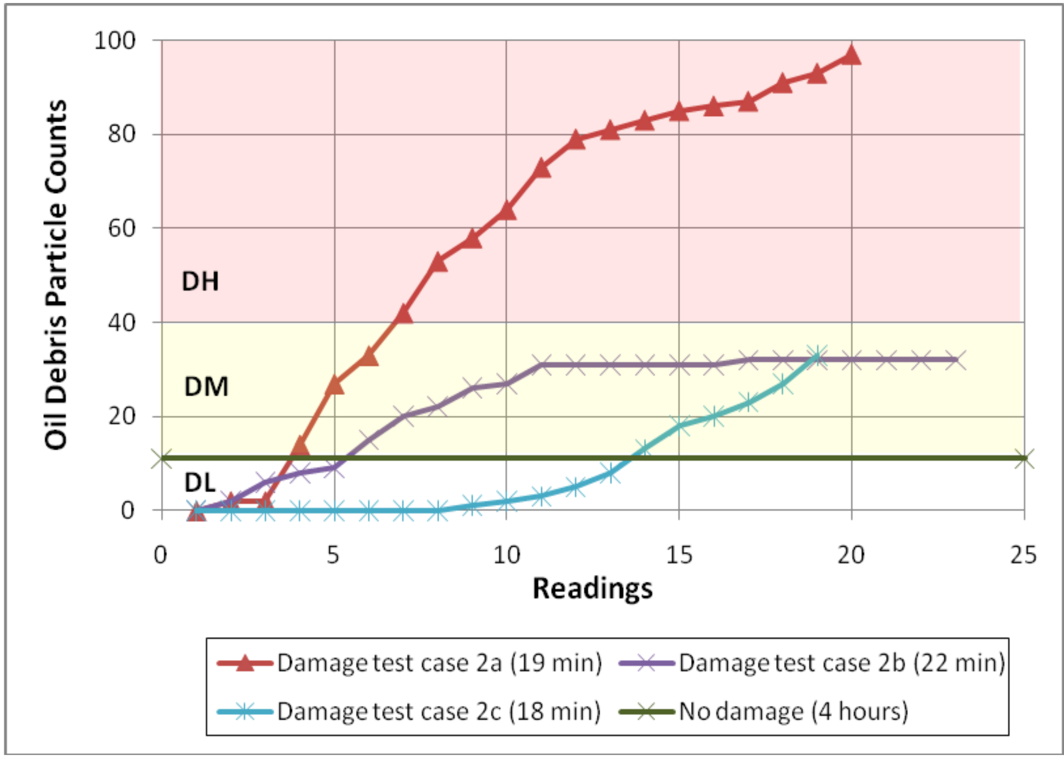
Gearbox Oil Condition Monitoring

- Typical practices
- Discussions



Typical Practices

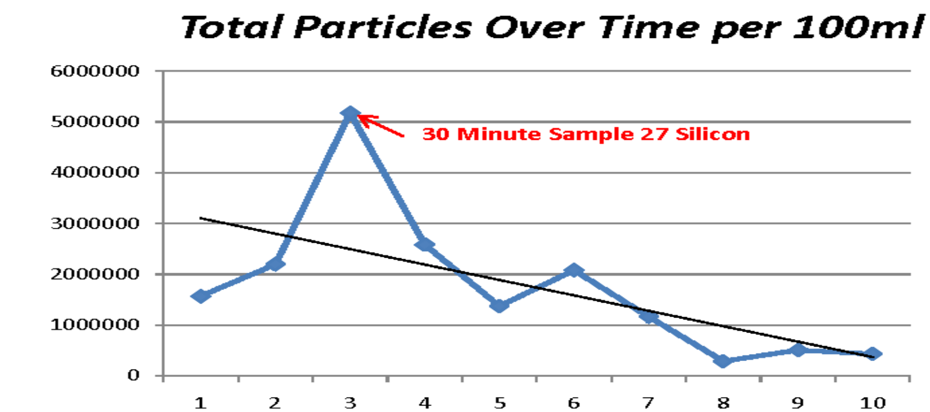
- Offline oil sample at 6-month interval
- Inline or online oil debris monitoring
- Oil cleanliness level measurements
- Filter element analysis



Sample Oil Debris Counts [13]

Oil Sample Analysis [14]

- Results: dynamometer test of the reference gearbox
  - Particle counts: important to identify particle types



ISO 4406 Code

21/17/12
22/18/12
23/22/20
22/21/16
21/18/13
22/18/12
21/17/12
19/15/11
20/17/10
19/17/13

  - Element identification

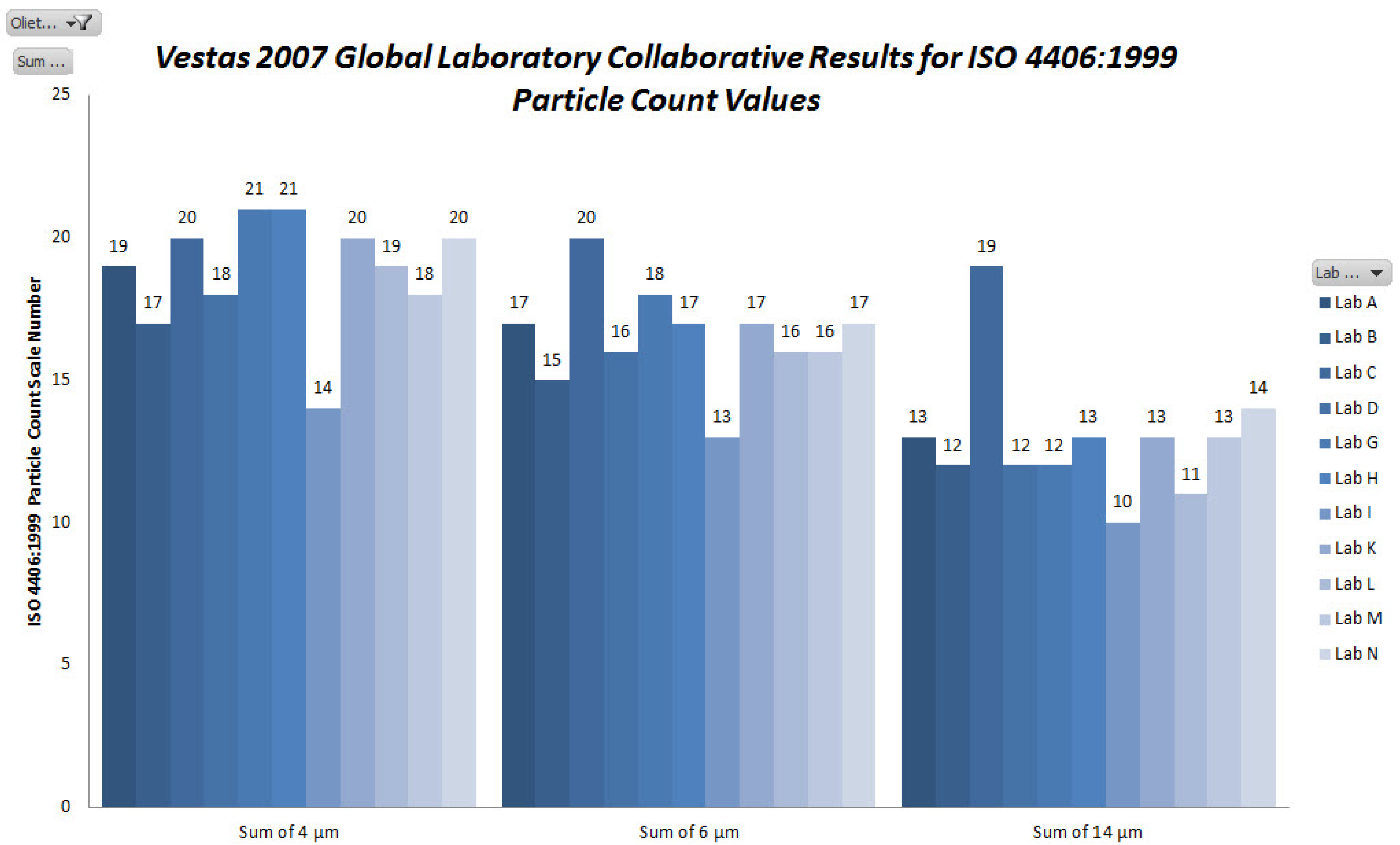
Metals		Reference Limits	Analysis Results					
Iron ppm		2	<1	1	1	1	1	1
Aluminum ppm		4	<1	<1	<1	<1	<1	<1
Chromium ppm		4	<1	<1	<1	<1	<1	<1
Copper ppm		2	<1	1	1	1	1	1
Lead ppm		1	<1	1	1	1	1	1
Tin ppm		4	<1	<1	<1	<1	<1	<1
Nickel ppm		4	<1	<1	<1	<1	<1	<1
Silver ppm		4.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Silicon ppm		20	<1	3	4	3	3	5
Sodium ppm			<2	<2	<2	<2	<2	<2
Boron ppm			<1	2	2	1	1	1
Zinc ppm			1	21	24	24	24	29
Phosphorus ppm			4	31	38	31	31	54
Calcium ppm			11	24	27	23	24	24
Magnesium ppm			<1	<1	<1	1	<1	<1
Barium ppm			3	8	9	6	7	7
Molybdenum ppm			<1	11	12	11	11	12
Potassium ppm			<3	<3	<3	<3	<3	<3

Reference Limits

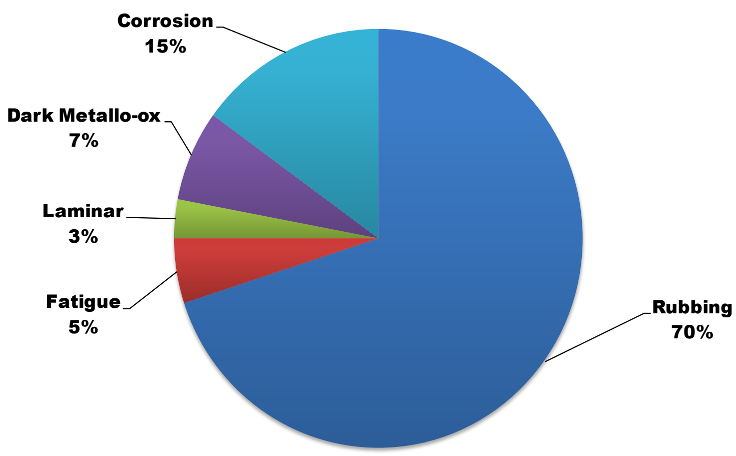
Analysis Results

Lab Analysis Variance [15]

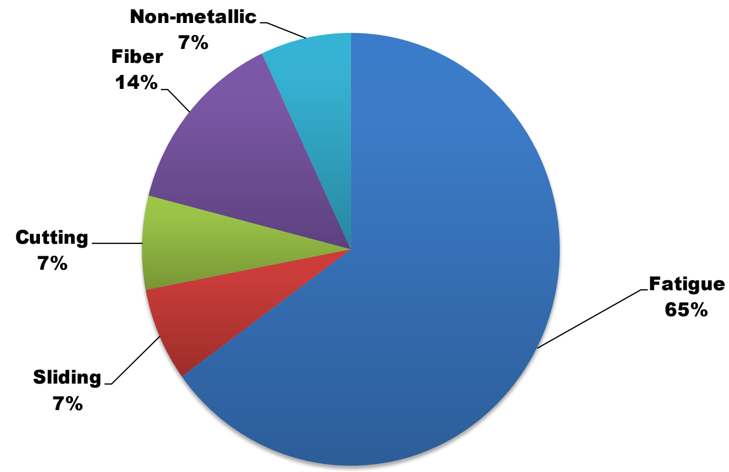
Interpreting ISO 4406 particle count values from gear oil samples taken in service



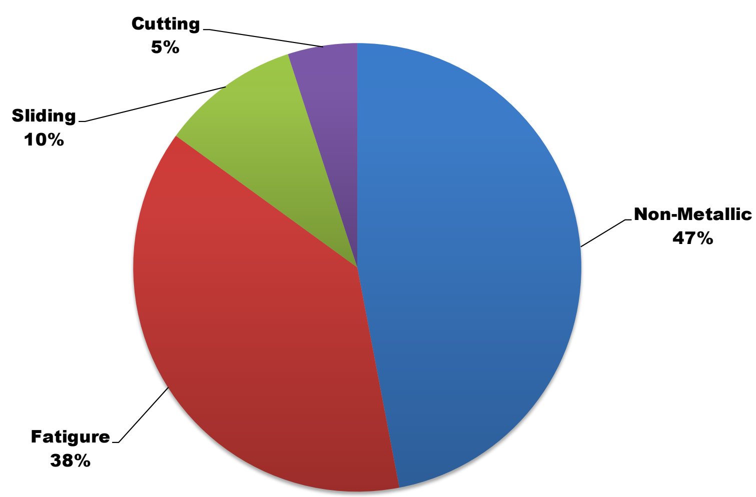
Failure Modes Identified by Different Methods [16]



(a) AFG

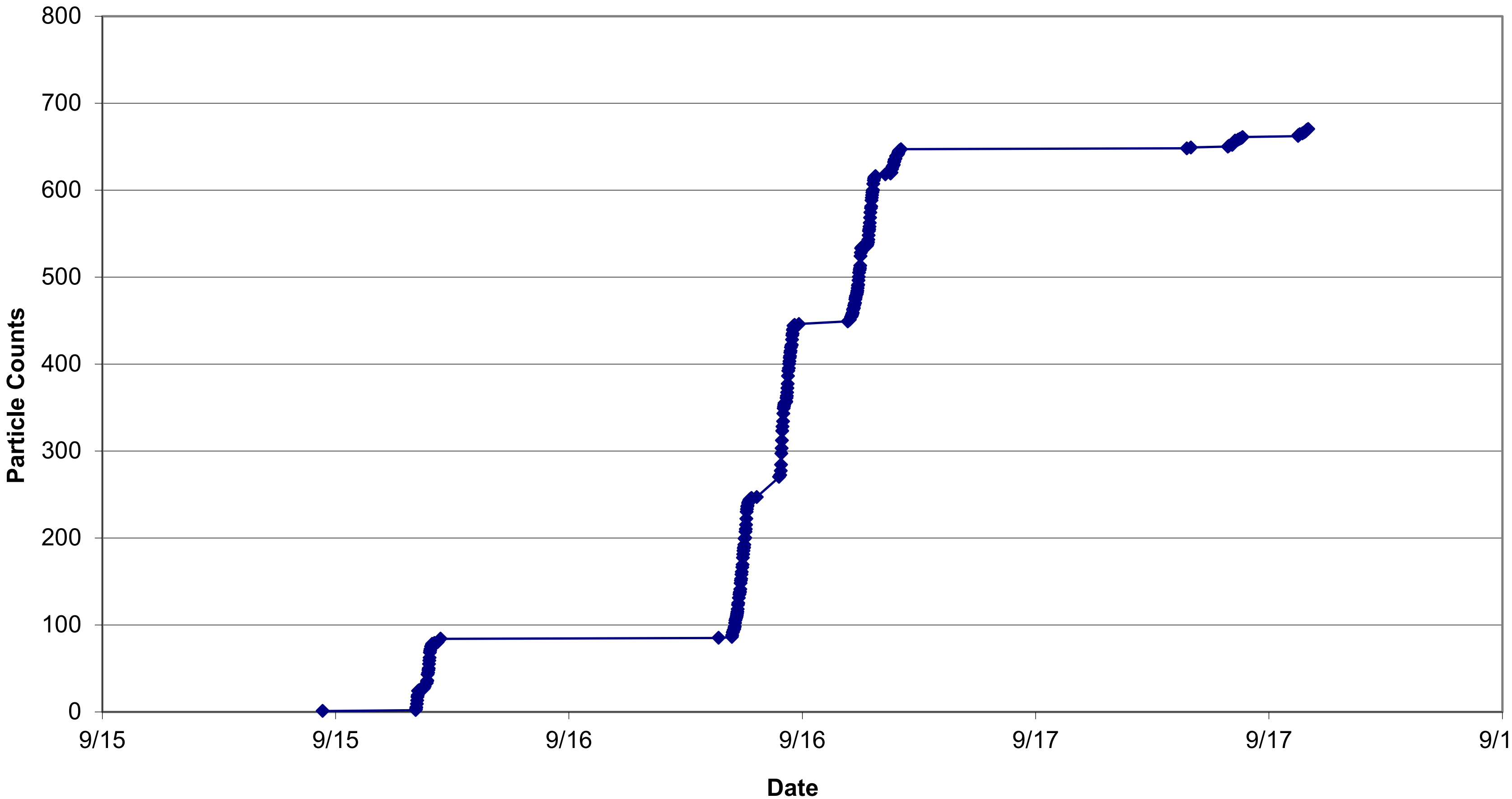


(b) LNF



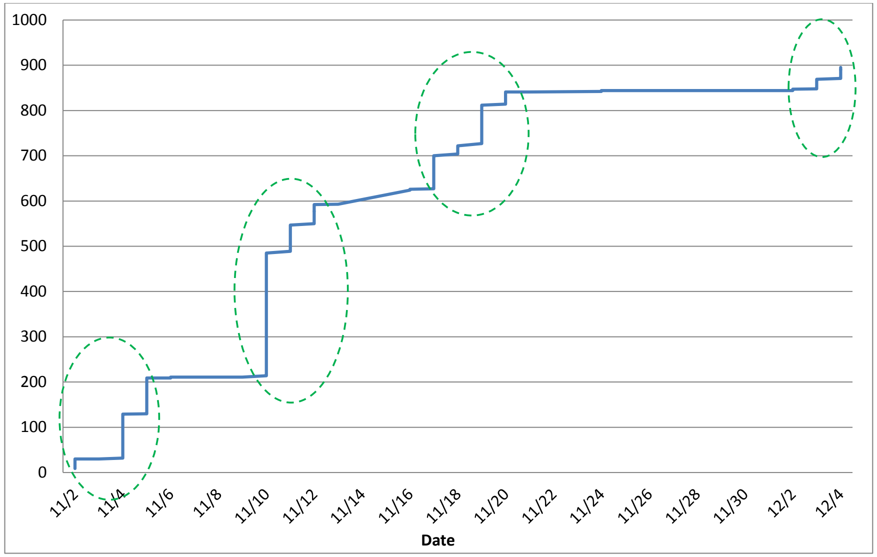
(c) SEM

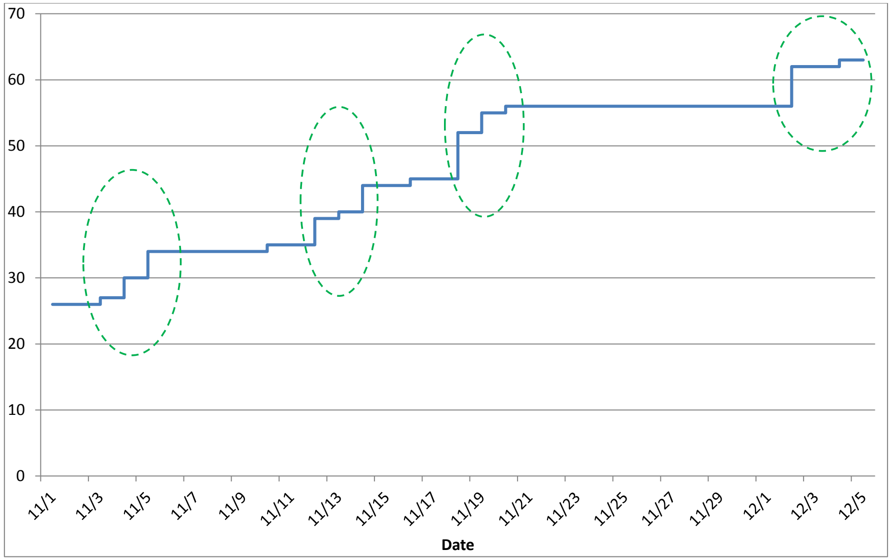
Oil Debris Monitoring: K1 [16]

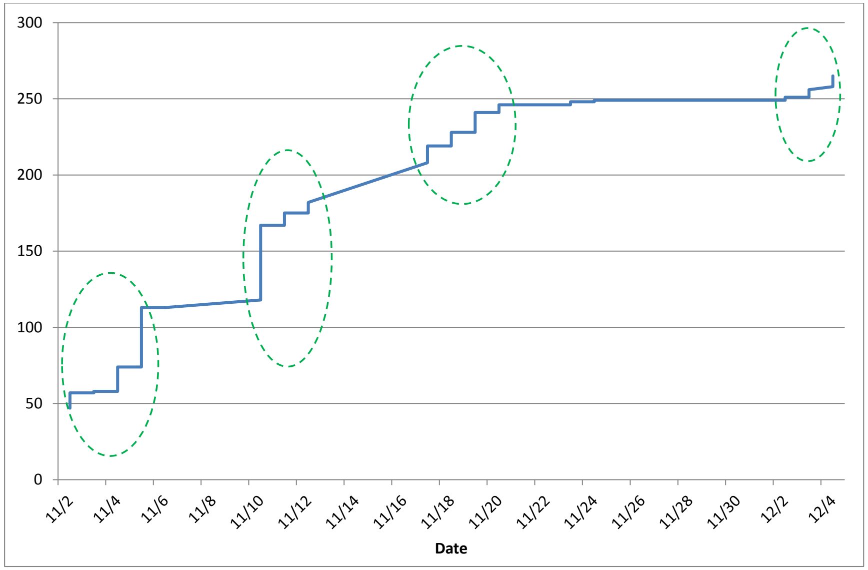


- Particle generation rates:
  - Damaged test gearbox: 70 particles/hour on 9/16/2010
  - Healthy reference gearbox: 11 particles over a period of 4 hours

Oil Debris Monitoring: K1~K3 [16]

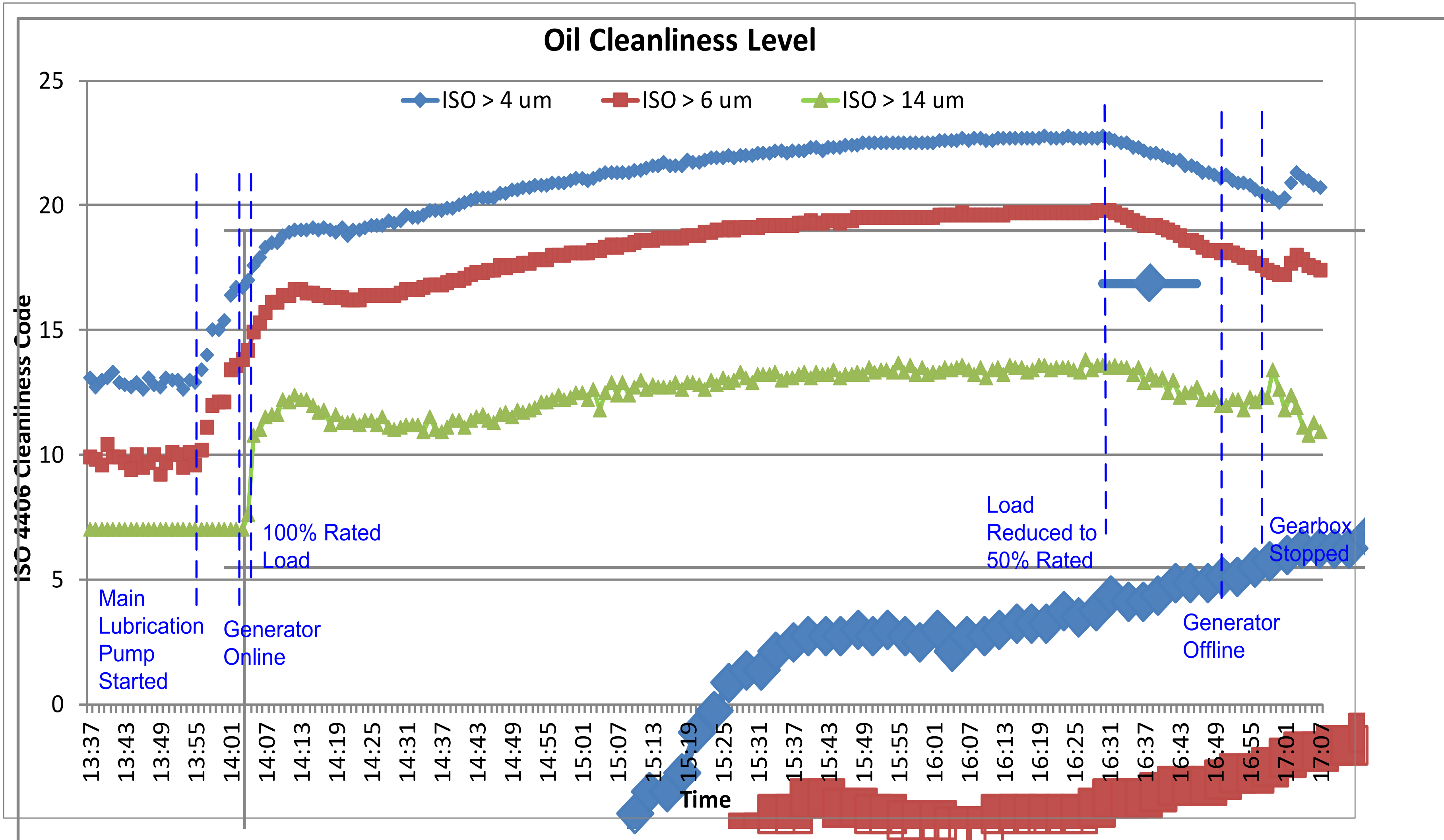




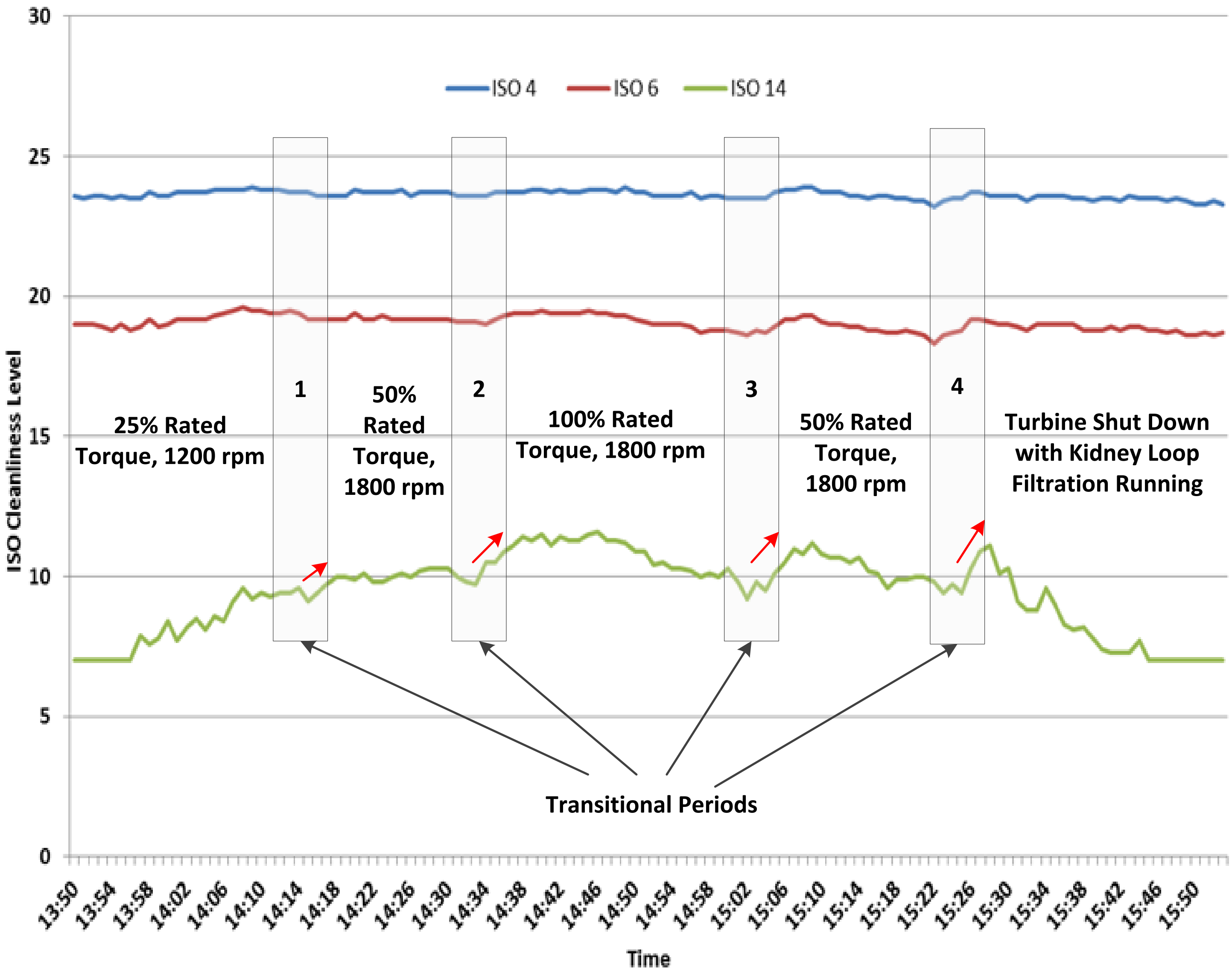


- Main-loop and offline-loop sensors
  - Similar trends
  - Different absolute values: sensor mounting location impacts

Oil Cleanliness Measurement: K4 [16]



Oil Cleanliness Measurement: K4 (Cont.) [16]



Filter Element Analysis [17]

- Direct reading ferrography results normal
- Important spectrometer results (ppm): Fe = 22, Cu = 36, Zn = 1621 (Additive masks alloy)
  - Hard to conclude the debris includes brass and steel
- Filter element analysis
  - Indicated high level of brass and steel
  - Uncovered what might not be detectable by a conventional oil sample analysis

Classification Rules

Classification	Rule
Barium	Ba >40%
Brass	Cu + Zn >40% and Cu >10%
Zinc	Zn >40%
Iron Oxide	Fe >30% and O >15%
Steel	Fe >30%
Additives	S + P + Zn >50%
Silicates	Si >5%
Miscellaneous	All remaining particles

Main Loop Filter Element Analysis

Element	Brass	Zinc	FeO	Steel	Total
Cr	0.0	0.1	0.0	2.2	0.2
Mn	0.1	0.1	0.3	0.1	0.1
Fe	0.8	2.9	59.9	81.8	8.9
Co	0.1	0.5	0.3	0.6	0.2
Ni	0.3	0.5	0.7	0.9	0.4
Cu	46.6	4.5	1.5	1.7	39.6
Zn	38.5	57.5	3.6	5.4	35.1

Discussions

- Periodic oil sample analysis may help pinpoint failed component and root cause analysis
  - When obtaining particle counts through oil sample analysis, attention should be given to identifying particle types
  - Variation in analysis results among laboratories
  - Inconsistent terminologies used in failure modes
- Oil debris monitoring is effective for monitoring gearbox component damage, but not for pinpointing locations
  - Damaged gearbox releases particles at increased rate
  - Main loop and offline loop with similar trends
- Oil cleanliness level measurements can be used to control run-in of gearboxes and highlight impacts from transient events
- Filter element analysis may reveal what is typically missed in conventional oil sample analysis

Future R&D Opportunities

- Investigate cost-effective solutions for oil filtration and CM with supporting evidence to address limitations in current practices
  - Develop industry standards to minimize discrepancies in laboratory analysis results and terminologies
  - Economical filter analysis methods
- Automate data interpretation to deliver actionable maintenance recommendations
- Develop reliable and accurate prognostic techniques
- Investigate improved technologies by targeting offshore wind applications: saltwater, even lower accessibility, etc.

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Thanks for Your Attention!

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